Single Top Quark Physics at the Tevatron and Beyond

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For the LHC part, valuable help received from:

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Dugan O'Neil, Simon Fraser Univ., ATLAS

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Single Top Production

- **Why look for single top:**
  - ↗ Cross section $\sim |V_{tb}|^2$: the only way to directly measure CKM matrix el. V_{tb}
  - ↗ Single top is background to other signals: e.g. Higgs searches.
  - ↗ Test non-SM phenomena:
    - ➢ Heavy W' boson
    - ➢ Anomalous Wtb couplings
    - ➢ FCNC couplings tug or tcg

- **At the Tevatron relevant channels are:**
  - ↗ t-channel W-gluon fusion:
    - ➢ 1.98 pb at $\sqrt{s}=1.96$ TeV
    - ➢ Hard b-jet, W decay products, soft b (usually lost), light quark jet
  - ↗ s-channel W*:
    - ➢ 0.88 pb at $\sqrt{s}=1.96$ TeV
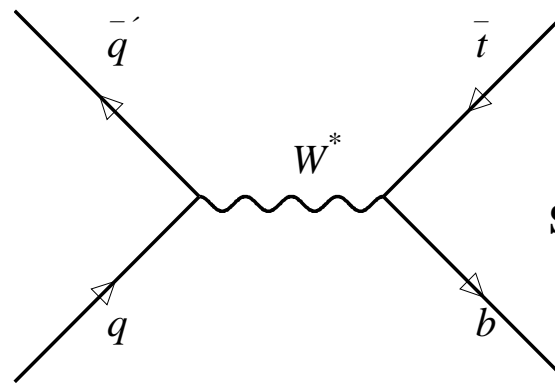   - ➢ Two hard b-jets, W decay products

  - ↗ *B.W. Harris et al.: Phys. Rev. D 66, 054024 (theoretical calculations)*

W-gluon fusion process
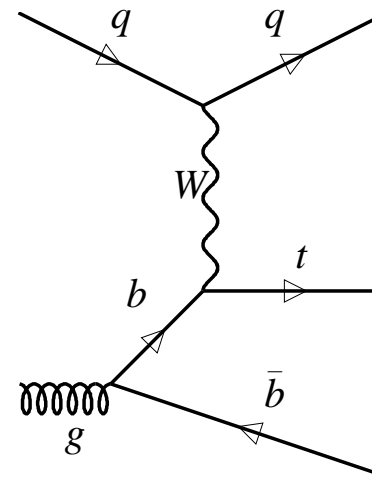
Signal is W+b+q

s-channel W* process

Signal is W+b+b̄

From Run I to Run II

- Results at $\sqrt{s}$ = 1.8 TeV from CDF and D$\varnothing$:
  - ↗ Single top has not been observed; 95% CL limits were set:
  - ↗ t-channel: D$\varnothing$ limit: **22** pb, CDF limit: **13** pb (theoretical x-section: **1.40** pb)
  - ↗ s-channel: D$\varnothing$ limit: **17** pb, CDF limit: **18** pb (theoretical x-section: **0.76** pb)
  - ↗ combined s- and t- channels search: CDF limits: 14 pb (H_T , M_{lnb})
  - ↗ most recent Run 1 CDF study finds a 2.2σ excess and limit of 24 pb (7-inp NN)
  - ↗ D$\varnothing$:Phys. Lett. B 517, 282 (2001); CDF: PRD65, 091102 (2002), C. Ciobanu's Ph.D. thesis

- For Run II:
  - ↗ Higher rate: 32% increase in the combined s and t channel x-section:
    - ➢ still small: 2.9 pb versus 6.7 pb for top pair production
  - ↗ More luminosity – right now CDF has 180 pb^{-1} – that is 70% more data!
  - ↗ Better detector acceptance
  - ↗ Preliminary CDF analysis done for 107 pb^{-1} of data:
    - ➢ Search for s- and t-channels combined production
    - ➢ Seaparate search for t-channel

Combined Search

- Look in the W+2 tight jets channel:
  - ↗ "tight" jet: E_T > 15 GeV, $|\eta|$ < 2.8
  - ↗ at least one SVX B-tag
  - ↗ exactly one lepton with E_T>20 GeV, $|\eta|$<2.0
  - ↗ missing energy: $\not{E}_T$>20 GeV
  - ↗ veto Z's, dilepton events
  - ↗ apply a top mass window cut: 140 < M_{lnb} <210 GeV/c^2

- Monte Carlo samples:
  - ↗ single top signal:
    - ➢ Pythia (1M events)
    - ➢ Madevent+Pythia (~200k)
  - ↗ HERWIG tt background
  - ↗ ALPGEN+HERWIG Wbb used to model the shapes of the non-top backgrounds: Wbb, Wcc, Wc, mistags, non-W events

Expected Yield

- For L=107.1 pb^{-1}:
  - ↗ expect 2.4 signal events
  - ↗ expect 16.1 backgrd events
  - ↗ observe 19 (expect 18.5)
- The variable with the most discrimination power is H$_T$, the total transverse energy in the event:
  - ↗ Will fit the H$_T$ shape in data as the sum of weighted MC shapes.
  - ↗ Use maximum likelihood method with Gaussian background constraints

Process	N in 107.1 pb^{-1}
W-gluon	**1.61 $\pm$ 0.51**
W*	**0.80 $\pm$ 0.18**
tt	**2.33 $\pm$ 0.70**
Wbb	**3.5 $\pm$ 1.5**
Wcc	**1.4 $\pm$ 0.8**
Wc	**3.1 $\pm$ 1.0**
Mistags	**2.9 $\pm$ 0.9**
Non-W	**2.2 $\pm$ 0.7**
Diboson	**0.7 $\pm$ 0.2**
Z+bb	**0.07 $\pm$ 0.03**
Total non-top	**13.8 $\pm$ 2.8**

Fitting H_T distributions

- ## H_T distributions for signal and backgrounds:
  - ↗ signal shapes similar for s- and t- channels
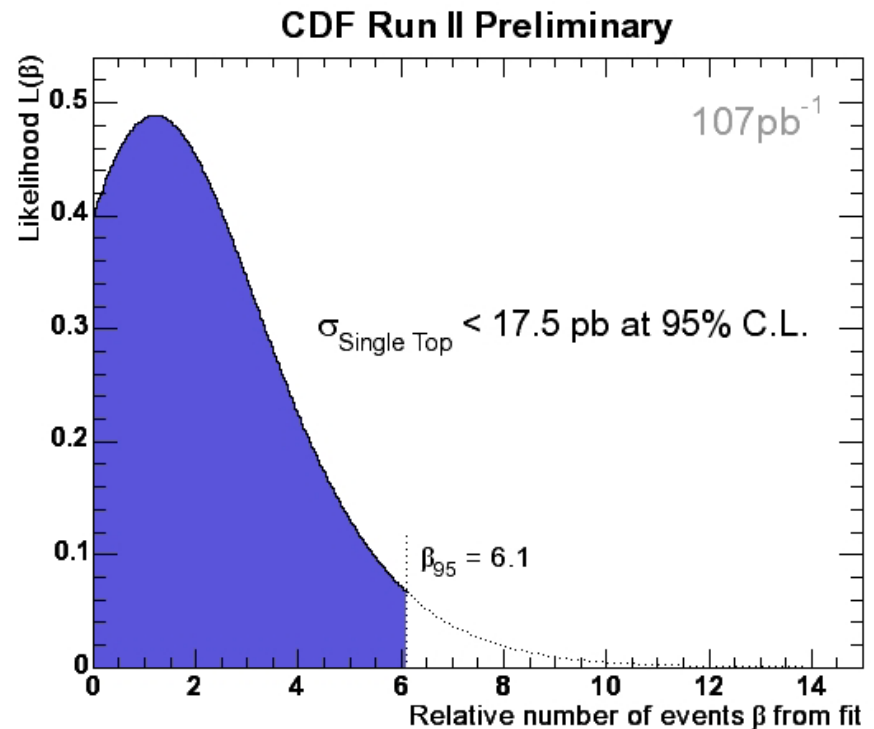 - ↗ fit yields 2.9±4.5 signal events (exp. 2.4 events).
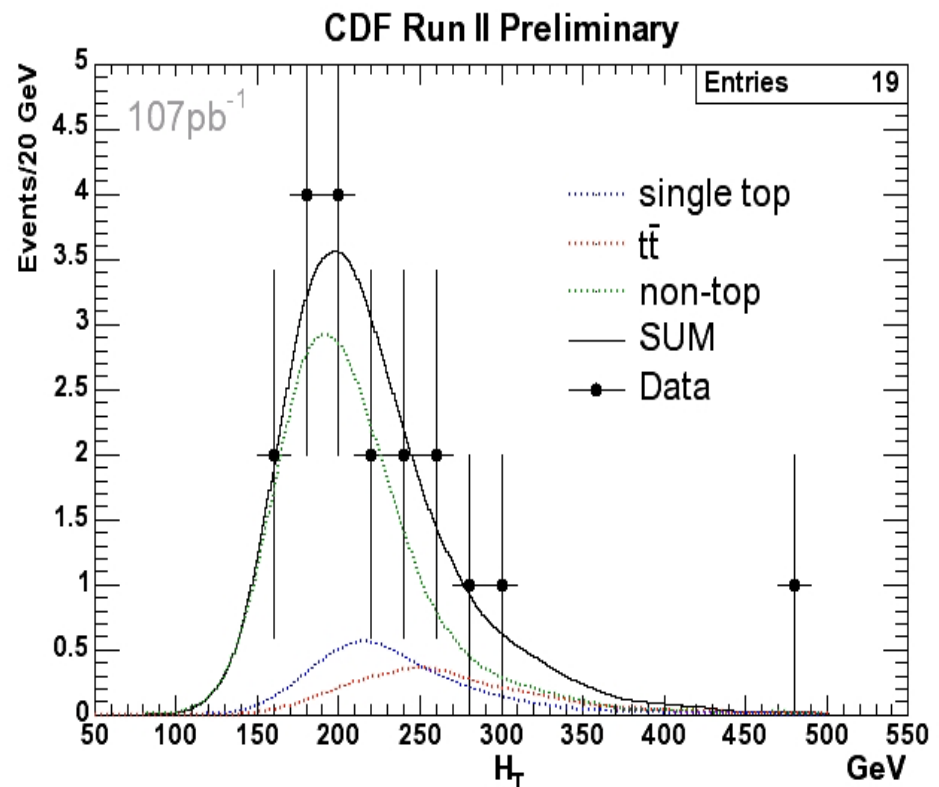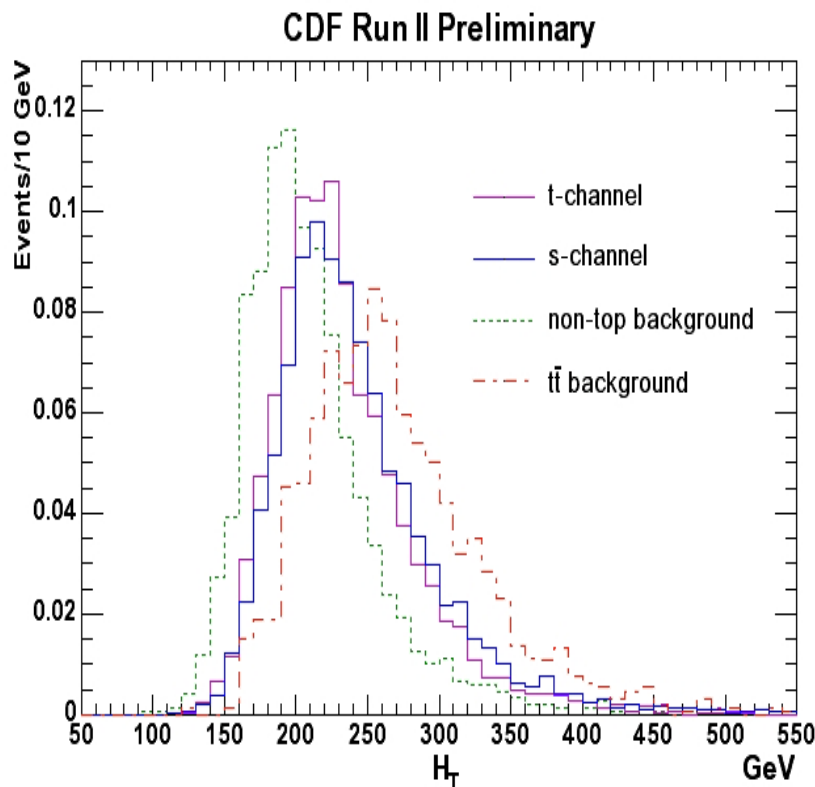
95% C.L. limit

- Limit at 95% C.L. is 17.5 pb
- This accounts for the systematics:
  - ↗ Jet E_T scale: 20.9%
  - ↗ ISR/FSR: 4.0%
  - ↗ Top Mass: 6.2%
  - ↗ PDF, signal generator, background model 1-2%

- Compare to Run I:
  - ↗ Same luminosity 107 vs 106 (pb^{-1})
  - ↗ 14 pb limit for 2.16 pb x-section
  - ↗ Now: 17.5 pb limit for 2.86 pb x-s.

    marginally better limit!

  - ↗ Several ways to improve this will be discussed later.

CDF Run II Preliminary

107pb^{-1}

$\sigma_{Single\ Top}$ < 17.5 pb at 95% C.L.

β_{95} = 6.1

Likelihood L(β)

Relative number of events β from fit

Separate Search

- Looking for the two signal channels individually is desired:
  - ↗ Different sensitivities to new physics:
    - ➢ s-channel: heavy charged vector bosons W', CP-violation effects within MSSM, Kaluza-Klein excited W-boson within MSSM
    - ➢ t-channel: FCNC couplings, anomalous V+A contributions to the W-t-b vertex, etc.
  - ➢ To go back to extracting V_{tb} we will have to know the individual rates

- We use the same selection as in the combined search.
  - ↗ However, using H_T is no longer appropriate
  - ↗ A variable with good W* - W-gluon separation potential is $Q \times \eta$, where Q is the lepton charge and η the pseudorapidity of the non-b jet.
  - ↗ Now treat W* as a background, therefore perform a 4-component fit

Fitting Q×η

- t-channel exhibits an asymmetry toward Qxη positive values (twice as many events than in the negative Qxη range)

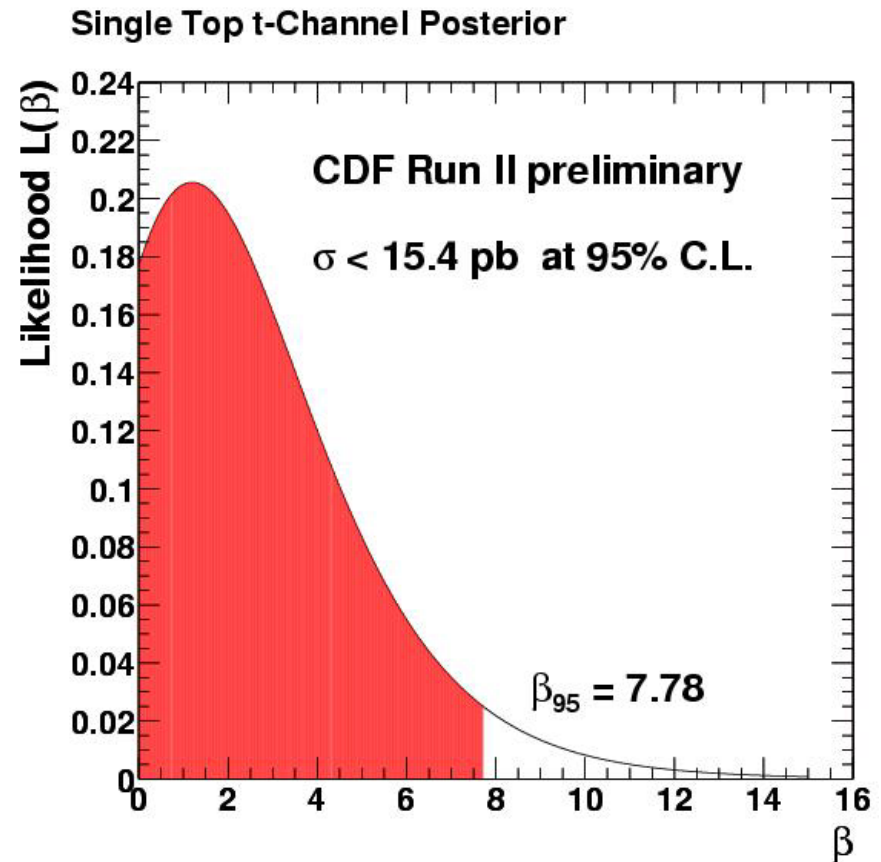- fit to data yields: 1.9± 3.7 t-channel signal events (exp. 1.6 events).
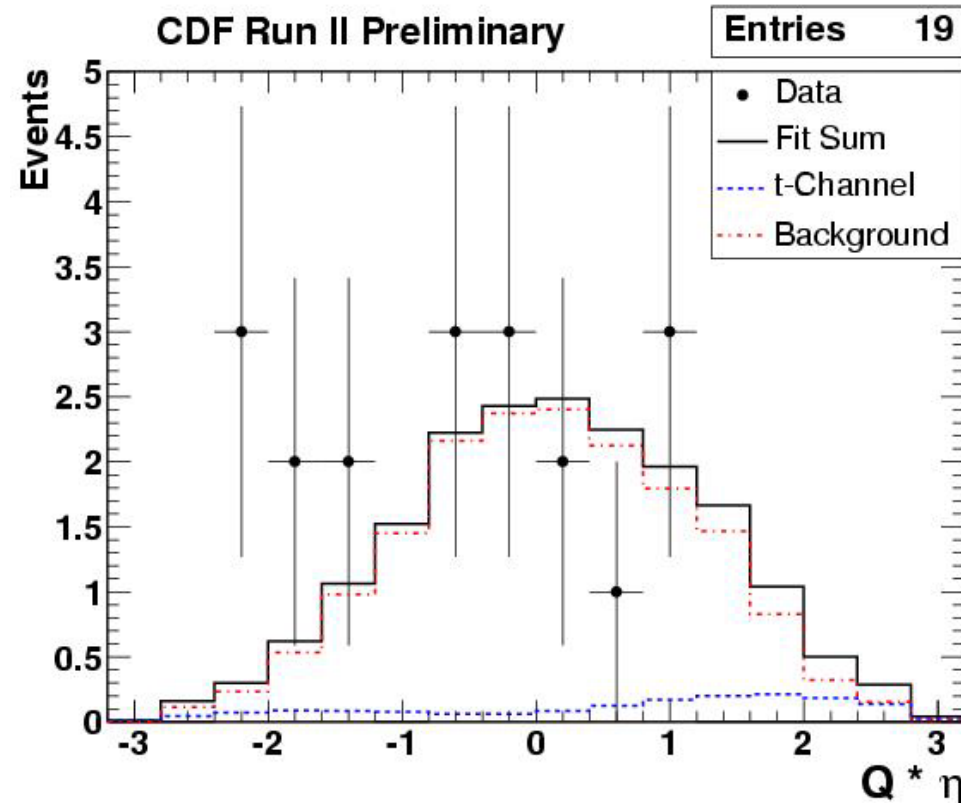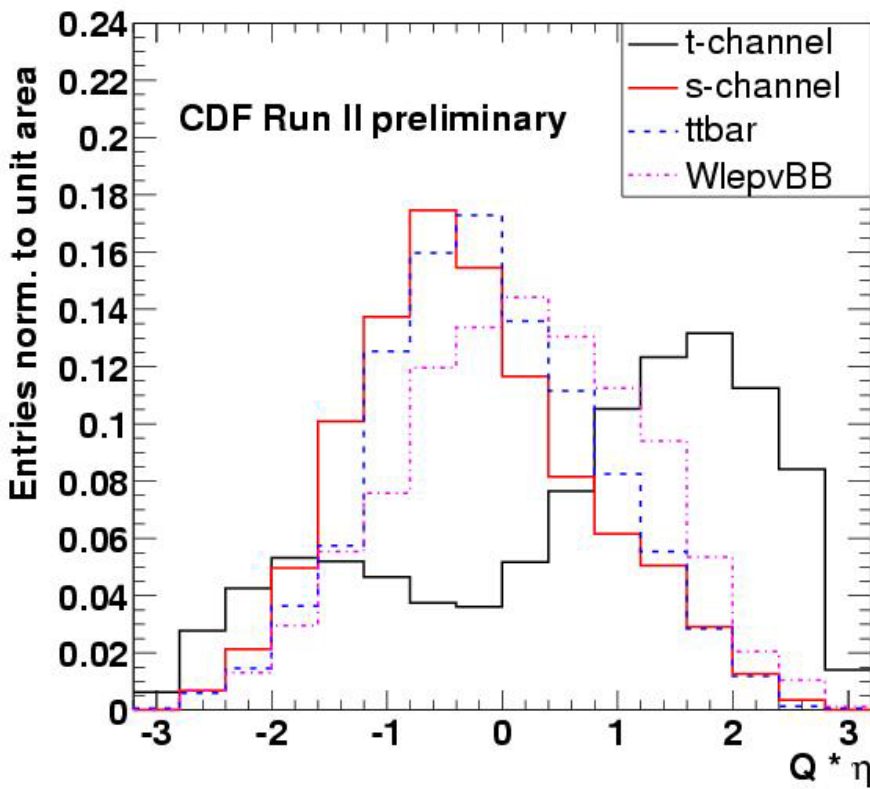
95% C.L. limit

- **Limit at 95% C.L. is 15.4 pb**
- **This accounts for the systematics:**
  - ↗ Jet E_T scale: 21.5%
  - ↗ Signal generator: 21.1%
  - ↗ Background model: 43.0%
  - ↗ ISR/FSR: 6.9%
  - ↗ Top Mass: 6.7%
  - ↗ PDF 4.3%

- **Compare to Run I:**
  - ↗ 13 pb limit for 1.40 pb x-section
 - ↗ Now: 15.4 pb limit for 1.98 pb x-s.

  again a better limit!

Single Top t-Channel Posterior

CDF Run II preliminary

$\sigma < 15.4$ pb at 95% C.L.

$\beta_{95} = 7.78$

Likelihood $L(\beta)$ vs β

Future Prospects

- In progress: Neural Network with 5 input variables: H_T, $E_T(j1)$, $E_T(j2)$, E_T, $P_T(j1\text{-}j2)$, Looking in the W+2j channel, no M_{lnb} cut
 Assuming the background uncertainties will scale as $L^{-1/2}$

Mean/RMS of Fitted $\sigma_{single\ top}$ as Function of L
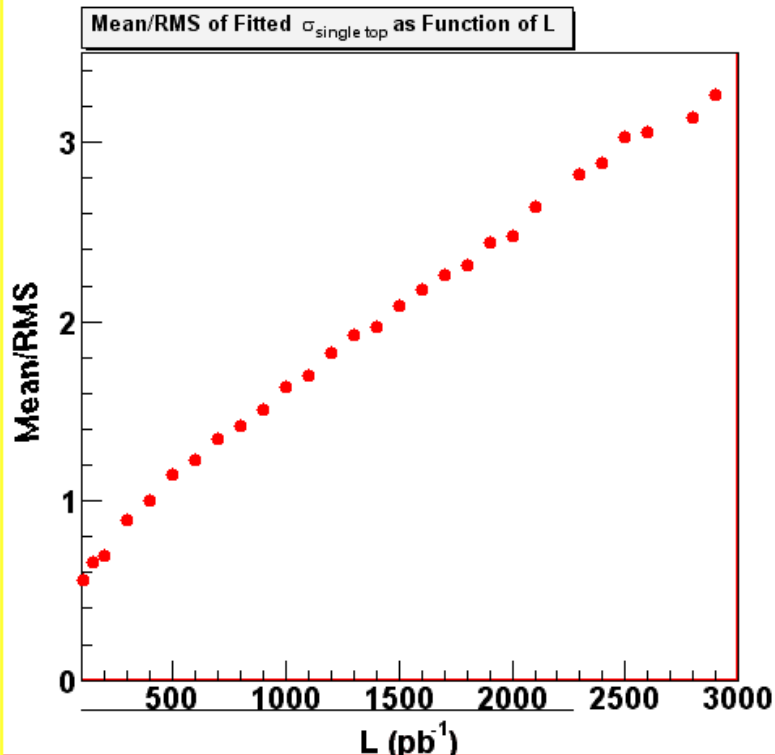
- Right now: 3 sigma with 2.5 fb^{-1}
- Improvements to come. We try:
  - ↗ Soft lepton tagger, Jet Prob. tagger
  - ↗ Use of forward electrons
  - ↗ Better discriminant variables:
    - ➢ Matrix elements (or ratios of these)
  - ↗ Use the top mass hypothesis to constrain the event
    - ➢ Will lead to better M_{lnb} resolution
  - ↗ Better understanding of the systematic uncertainties is crucial.

Single Top at the LHC

- **LHC will be a top quark factory:**
  - ↗ 8 million top pairs per experiment per year (10 fb^{-1} / year)
  - ↗ Some cross section values for $\sqrt{s}$ = 14 TeV:
    - ➢ top pair production: ~ 800 pb (mostly via gluon-gluon fusion)
    - ➢ t-channel single top: 153 (top) and 90 (antitop) = 243 pb
      - ➢ **e.g. per day ~6000 events, at 10^{33}cm^{-2}s^{-1}**
    - ➢ s-channel single top: 6.6 (top) and 4.8 (antitop) = 11 pb
    - ➢ associated Wt production: 50-60 pb
      - ➢ **Negligible at the Tevatron**

  - ➢ Will discuss each of the three modes in what follows
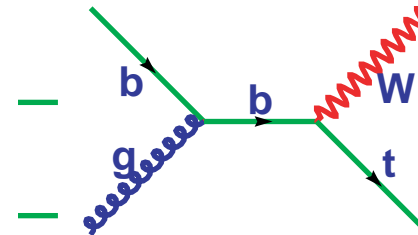
t-channel single top (CMS)

- **CMS study** (hep-ph/0003033):
  - ↗ Full calorimeter simulation + b-tag efficiency parametrization
  - ↗ Pythia 5.72 signal, tt, WZ; Vecbos+Herwig W+jets. Selection:
    - ➤ One isolated lepton with P_T>20 GeV/c, $|\eta|$<2.5
    - ➤ Missing E_T>20 GeV, 50 < $M_{l\nu}$ <100 GeV/c^2
    - ➤ Two jets with E_T > 20 GeV, $|\eta|$ < 4.0
      - ➤ **One jet: E_T > 20 GeV, $|\eta|$ < 2.5, the other E_T > 50 GeV, 2.5<$|\eta|$ < 4.0**
      - ➤ **Leading jet E_T<100 GeV (to reduce tt)**
      - ➤ **Exactly one b-tagged jet – the central one**
    - ➤ Reject WZ candidates with: 80 < M_{jj} <100 GeV/c^2
  - ↗ Signal peak visible in reconstructed M_{top} distribution
  - ↗ With 10 fb^{-1}, $\sqrt{(S+B)}/S$ = 1.4%
- **The quest continues – newer det. simulation**
  - ↗ use fancier generators: TopRex, Single Top
  - ↗ Work-in-progress, unofficial results $\delta\sigma / \sigma$ ~ 10%
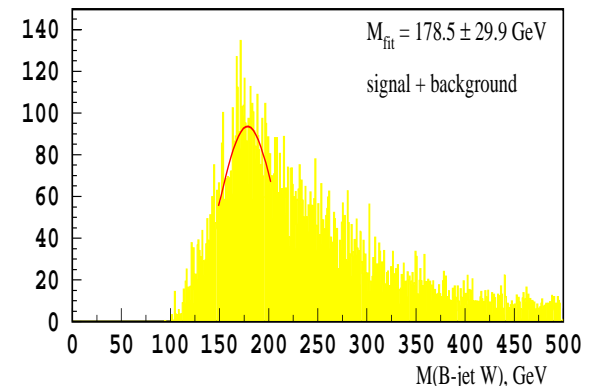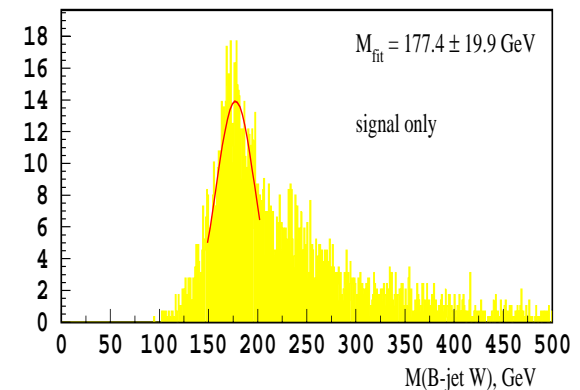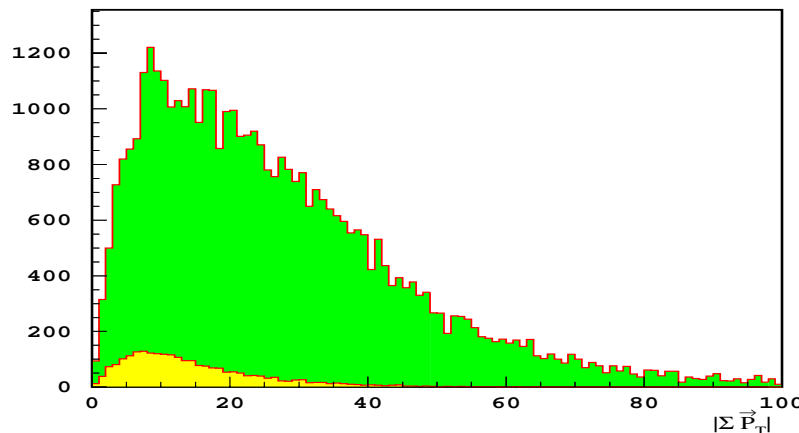
V.Abramov, CMS Week 9/17/03
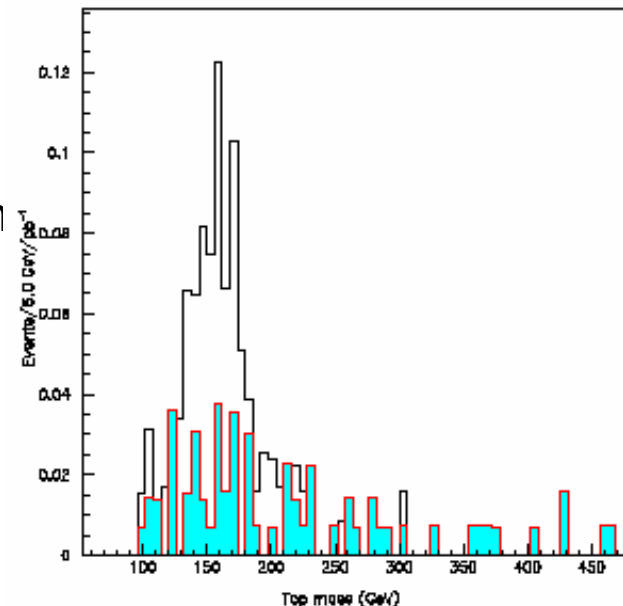
t-channel single top (ATLAS)

- **ATLAS study of W-gluon single top** (Dugan O'Neil's Ph.D. thesis):
  - ↗ ATLFAST parametrized detector simulation
  - ↗ Onetop+Pythia 5.72 signal, tt; M.E.+HERWIG Wbb, Wjj
  - ↗ Selections are rather similar to CMS study, plus:
    - ➤ $150 < M_{top} < 200$ GeV/c^2
  - ➤ Result: $\sqrt{(S+B)}/S = 0.9\%$ with 10 fb^{-1}.

- **What about V_{tb}? Extracting $|V_{tb}|^2$ from x-section picks up uncertainties:**
  - ↗ x-section uncertainty:
    - ➤ Statistical: 5% is a perhaps reasonable/optimistic guess for L=10 fb^{-1}
    - ➤ Systematic <20%. Here things can easily be off by a lot, especially in the 1st year…
  - ↗ Luminosity uncertainty: traditionally 4-5%
  - ↗ Theoretical uncertainty:
    - ➤ From factorization and renormalization scale dependence (3% from NLO calculation)

s-channel single top (CMS)

- **CMS study** (S. Sablospitsky, CMS week 9/17/03)
  - ↗ disclaimer: work-in-progress, not yet 'official' results
  - ↗ use TopRex to generate single top, tt, Wbb. Pythia W+jets. Use CMSJET 4.801
  - ↗ selection:
    - ➤ one lepton with $E_T > 10$ GeV, $|\eta| < 2.5$
    - ➤ 2 B-tags with $E_T > 20$ GeV, no other jets with $E_T > 20$ GeV
    - ➤ Vector sum all final state P_T: $|\Sigma \mathbf{P_T}| < 15$ GeV
    - ➤ Reconst. top mass: 150 GeV $< M_{top} < 200$ GeV/c^2
  - ➤ Results: $\sqrt{(S+B)}/S = 12\%$, S/B = 8% for L = 30 fb^{-1}
 - ➤ which implies $\delta|V_{tb}| = 8.3\%$

$M_{fit} = 177.4 \pm 19.9$ GeV

signal only

M(B-jet W), GeV

$|\Sigma \vec{P}_T|$

$M_{fit} = 178.5 \pm 29.9$ GeV

signal + background

M(B-jet W), GeV

s-channel single top (ATLAS)

- **ATLAS study** (hep-ph/0003033)
  - ↗ Onetop+Pythia 5.72 signal, tt; M.E.+HERWIG Wbb, Wjj
  - ↗ Selection:
    - ➢ One isolated lepton with P_T>20 GeV/c, $|\eta|$<2.5
    - ➢ 2 b-jets with E_T>75 GeV
    - ➢ Scalar sum all final state P_T: $|\Sigma P_T|$<175 GeV
    - ➢ Reconst. top mass: 150 GeV<M_{top}<200 GeV/c^2
  - ↗ Results: $\sqrt{(S+B)}/S$ = 5.5% for L = 30 fb^{-1}, $\delta|V_{tb}|$~1%

- **Wt single top production at ATLAS:**
  - ↗ 65< M_{jj} < 95 GeV/c^2
  - ↗ Event invariant mass < 300 GeV/c^2
  - ↗ $\sqrt{(S+B)}/S$=4.4% for L = 30 fb^{-1}
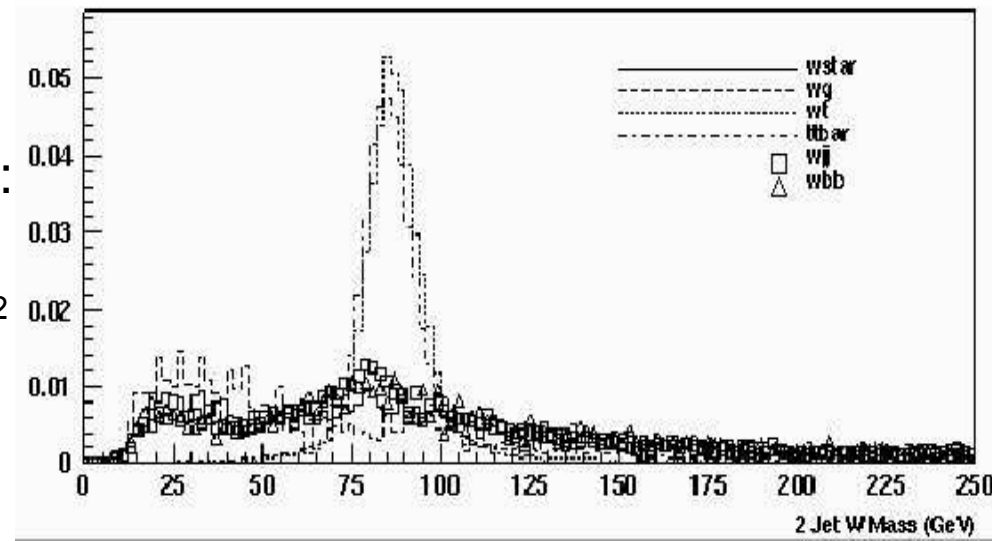
Top Polarization in Single Top Events

- EW-produced top quarks are highly polarized:
  - ↗ In the top rest frame, its spin points along the direction of the down (d) quark.
  - ↗ Restrict to t-channel single top:80% (69%) of the top (antitop) events have the 'd' quark in the final state. The angular distrib. of the charged lepton:

$$f(\cos\theta_\lambda) = \frac{1}{2}\left(1 + P\cos\theta_\lambda\right)$$

  - ↗ used signal samples with P=+1 and P=-1. Consider only W+jet background.
  - ↗ Chisquare fit, letting the two P contributions float.
  - ↗ The error on polarization measurement is 1.6% for 10 fb^{-1} (Dugan'sPh.D.thesis)
- W boson helicity measurement:
  - ↗ Again restrict to t-channel signal.
  - ↗ Measure $\cos(\psi_l)$ distribution. ψ_l between the direction of the lepton in W rest frame and the direction of the W in the top rest frame.
  - ↗ Three component fit: f_L , f_R , f_{Long} , with $f_L + f_R + f_{Long} = 1$
  - ↗ Uncertainties of the order 2-3% for 30 fb^{-1} of data.

Conclusions

- CDF and DØ accumulated more events than in entire Run I (factor of 2).
- Preliminary CDF study from 107 pb^{-1} sets promising single top limits
- However, many improvements needed if we are to observe single top in the next 2-3 years.
- Precision measurements of $|V_{tb}|$, as well as top polarization are not within (immediate) sight

- LHC will see very exciting results in the first (few) years of running:
  - ↗ 10 –30 fb^{-1} needed for observation in most searches.
  - ↗ Higher collider energy = considerable higher cross sections
- ATLAS and CMS single top studies are very mature
  - ↗ The Monte Carlo efforts are particularly strong: Top Rex, SingleTop.
- CDF/DØ can help with insight into systematics. Search strategies are already similar between Tevatron and CERN, but big improvements are just an idea away!